

Multiple CO Transitions, CI, and HCN from the Cloverleaf Quasar

Richard Barvainis

MIT Haystack Observatory, Westford, MA 01886 USA¹

Philip Maloney

CASA, University of Colorado, Boulder, CO 80309-0389 USA

Robert Antonucci

UC Santa Barbara, Physics Department, Santa Barbara, CA 93106 USA

and

Danielle Alloin

Service d'Astrophysique, L'Orme des Merisiers, CE Saclay, 91191, Gif-Sur-Yvette, Cedex, France

ABSTRACT

New millimeter-wavelength emission lines are reported for the Cloverleaf (H1413+117), a gravitationally lensed quasar at redshift 2.56. High signal-to-noise ratio spectra of four lines in CO ($J = 3 \rightarrow 2$, $4 \rightarrow 3$, $5 \rightarrow 4$, and $7 \rightarrow 6$) have been obtained and are modelled using an escape probability formalism. The line brightness temperatures are flat or rising between CO($3 \rightarrow 2$) and CO($4 \rightarrow 3$) and then drop to the CO($5 \rightarrow 4$) and CO($7 \rightarrow 6$) lines; this falloff suggests that the optical depths in the CO lines are modest ($\tau_{4-3} \lesssim 3$), and that the gas is relatively warm ($T \gtrsim 100$ K) and dense ($n_{\text{H}_2} \gtrsim 3 \times 10^3 \text{ cm}^{-3}$).

The neutral carbon fine structure line $\text{CI}(^3P_1 \rightarrow ^3P_0)$ was detected with moderate SNR on two separate occasions, and appears secure. The $\text{HCN}(4 \rightarrow 3)$ line is somewhat more tentative, as it was observed only once and detected with moderate SNR. However, its brightness ratio relative to the CO($4 \rightarrow 3$) line, $L'(\text{HCN})/L'(\text{CO}) \approx 0.25$, is very similar to the ratio seen in luminous infrared galaxies. This probably reflects the gas fraction maintained at high densities by radiation pressure from the active nucleus; alternatively, the HCN transition may be excited through absorption of infrared radiation at $14\mu\text{m}$.

The detectability of the Cloverleaf in molecular and neutral atomic transitions is largely due to high emissivity of the gas and magnification from gravitational lensing, rather than an extremely large mass of gas.

Subject headings: quasars: individual (H1413+117) — ISM: molecules

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1. Introduction

There are few observational windows on galaxies at high redshift, and each new one that opens up is invaluable. It is now possible to directly study interstellar gas in significant quantity in three systems at $z > 2$: IRAS F10214+4724 ($z = 2.28$), the Cloverleaf quasar H1413+117 ($z = 2.56$), and the quasar BR1202–0725 ($z = 4.69$). F10214+4724 was first identified as a luminous infrared galaxy (Rowan-Robinson et al. 1991), and has been detected in three transitions of carbon monoxide (Brown & Vanden Bout 1992a; Solomon, Downes, & Radford 1992a). It is now known both that this object is gravitationally lensed (e.g. Broadhurst and Lehar 1995), and that it harbors an obscured quasar nucleus seen in polarized (reflected) light (Goodrich et al. 1996). BR1202-0725, the third highest redshift quasar currently known, has recently been detected in CO by Ohta et al. (1996) and Omont et al. (1996). The Cloverleaf quasar, the subject of this paper, is a QSO with classical broad emission lines plus broad absorption troughs in the optical, with an image that is lensed into four spots separated by about $1''$.

Based on its strong submillimeter continuum emission, indicative of a large mass of cool dust (Barvainis, Antonucci, & Coleman 1992), the Cloverleaf presented a good candidate for the study of molecular gas at high redshift. Indeed, CO($3 \rightarrow 2$) line emission, redshifted to 97 GHz, was searched for and readily detected (Barvainis et al. 1994; Wilner, Zhao & Ho 1995). The close similarities in both infrared/submillimeter continuum and CO emission properties between the Cloverleaf and F10214+4724, and the fact that both have powerful active nuclei, have given rise to models uniting these two objects through orientation/obscuration effects (e.g., Barvainis et al. 1995; Granato, Danese, & Franceschini 1996), and have bolstered evolutionary scenarios linking luminous infrared galaxies and quasars in general (e.g., Sanders et al. 1988; Wills et al. 1992).

To provide more information on the state of the interstellar medium in the host galaxy of the Cloverleaf, we have obtained detections in three new transitions of CO, and have made measurements in two transitions of neutral carbon and one of HCN. We present these results, together with models for the emitting gas, below.

2. Observations and Results

The observations were carried out using the IRAM 30m telescope on Pico Veleta, Spain, during observing runs in 1994 June (two nights) and 1995 May (seven nights), and with the Plateau de Bure Interferometer (PdBI), near Grenoble, France, during 1996. At the 30m the weather was mainly clear during both runs, but occasional high winds during the 1995 run resulted in some downtime. Spectral data were obtained in the 3mm, 2mm, and 1mm bands simultaneously, using SIS mixer receivers and filterbank or acousto-optical backends of 512 MHz bandwidth. System temperatures derived using the chopper wheel method were typically 250 K, 200 K, and 400 K in the 3mm, 2mm, and 1mm bands respectively. Double position switching was employed to provide flat baselines, with subreflector nutation at a rate of 0.5 Hz.

Clear detections were obtained in four CO transitions: $J = 3 \rightarrow 2$, $4 \rightarrow 3$, $5 \rightarrow 4$, and $7 \rightarrow 6$. Peak antenna temperatures were in the range 4–8 mK. $^{13}\text{CO}(3 \rightarrow 2)$ was searched for but not detected. A similar line flux and velocity width for the $J = 3 \rightarrow 2$ line was obtained by Wilner et al. (1995). The $\text{CO}(7 \rightarrow 6)$ single-dish measurement presents a problem, because of the limited available bandwidth of 512 MHz. Corresponding to 680 km s^{-1} at 226 GHz, this is not wide enough to provide a zero-level baseline – even with subreflector nutation the zero level in the raw spectrum cannot be trusted. We will therefore instead use here the PdBI observations of $\text{CO}(7 \rightarrow 6)$ (for details, see Alloin et al. 1997). These also suffer from the same limited bandwidth, but for interferometer observations the zero level should be accurate. To derive the total intensity (Jy km s^{-1}) of the line for comparison with the other CO transitions it is necessary to fit the line with a gaussian, but the line width is poorly constrained since the line wings are cut off at the band edges. Fixing the linewidth to the mean of the other three CO transitions, $\Delta V_{\text{FWHM}} = 376 \text{ km s}^{-1}$, we obtain $I_{\text{PdBI}} = 43.7 \pm 2.2 \text{ Jy km s}^{-1}$ (the error is statistical only, and does not include 10% calibration uncertainty).

The spectra are shown in Figure 1, in units of flux density. Table 1 gives line parameters and upper limits as derived from Gaussian profile fits to the 30m spectra [except for $\text{CO}(7 \rightarrow 6)$, where the line parameters are estimated as described above]. The line luminosities are given in two ways: L , in units of solar luminosities, and L' in units of $\text{K km s}^{-1} \text{ pc}^2$ (see Solomon, Downes, & Radford 1992a for definitions and formulae for computation). L' is proportional to line brightness (Rayleigh-Jeans) temperature integrated over the area of the source, and assuming that the CO lines arise in the same general volume this quantity can be used to form line brightness temperature ratios to constrain physical conditions in the gas (see below).

Observations were also made of the neutral carbon fine structure lines $\text{CI}(^3P_1 \rightarrow ^3P_0)$ and $\text{CI}(^3P_2 \rightarrow ^3P_1)$ (rest frequencies 492.161 GHz and 809.343 GHz, respectively). A detection in the former made in the 1994 run repeated with reasonable consistency in 1995, and the average of all good scans from both years is shown in Figure 1. Confidence in this detection is enhanced by the similarity in redshift and line shape to the CO lines (Table 1). Also, the line repeated after a shift in observing frequency which placed it in a different part of the filterbank. In $\text{CI}(^3P_2 \rightarrow ^3P_1)$, only an upper limit was obtained (Table 1).

Finally, we observed $\text{HCN}(4 \rightarrow 3)$ during the 1995 run. We report a tentative detection of a line with peak flux density of 5.5 mJy (Figure 1). The total integration time for this observation was about 30 hours. Although this line is near the limit of detectability for the 30m telescope, as in the case of $\text{CI}(^3P_1 \rightarrow ^3P_0)$ we are encouraged by the similarity of the line parameters to those of CO.

Some comments on the uncertainties in the observed line ratios are in order. In addition to the formal errors from noise in the measurements, it is necessary to include the systematic errors. Conversion from antenna temperature in Kelvins to flux density in Janskys was done using standard calibration factors for the 30m telescope derived from observations of planets and

other standard sources. The errors in these factors are estimated to be $\pm 10\%$ for the $3 \rightarrow 2$ line and $\pm 15\%$ for the $4 \rightarrow 3$ and $5 \rightarrow 4$ lines (C. Kramer, private communication). For the PdBI observations of CO($7 \rightarrow 6$) the calibration uncertainty is estimated at 10%. Including the systematic and statistical errors, the CO line Rayleigh-Jeans brightness temperature ratios relative to the strongest line, CO($4 \rightarrow 3$), are then: $(3-2)/(4-3) = 0.83 \pm 0.16$, $(5-4)/(4-3) = 0.73 \pm 0.16$; $(7-6)/(4-3) = 0.68 \pm 0.13$. These ratios are computed from the L' values given in Table 1.

3. Interpretation

3.1. The CO lines

The CO lines are characterized by a constant or increasing brightness temperature in going from $J = 3 \rightarrow 2$ to $J = 4 \rightarrow 3$, followed by a decrease in the higher- J transitions. We cannot rule out the possibility that the brightness temperatures are the same for all transitions, since the line ratios differ from predicted thermal R-J values by only $1.5 - 2\sigma$ in each case. In the case of thermal line ratios we would be able to say little about the column density or temperature of the gas. However, below we will assume that our measured values represent the true line brightnesses, and use them to model physical conditions in the gas. This exercise suggests that the line optical depths are modest, with $\tau \sim$ a few or less.

In modeling the CO line ratios, we calculate the excitation of the CO molecules using a non-LTE scheme which employs mean escape probabilities to include the effects of radiative trapping on the excitation of the CO (cf. Aalto et al. 1991); the results depend on the density n of H_2 , the gas kinetic temperature T , and the CO column density per unit linewidth $N_{CO}/\Delta V$. We note in passing that in non-LTE models using the essentially equivalent LVG approximation, the ratio of CO abundance to velocity gradient – which fixes the optical depths – is often set to a value appropriate to Galactic molecular clouds (e.g., Solomon, Downes, & Radford 1992a), which is not *a priori* justifiable when the physical conditions in the gas may be radically different.

In Figure 2 we show the allowed ranges in n and $N_{CO}/\Delta V$ for three temperatures, $T = 60$, 100, and 300 K; the allowed ranges are the hatched regions within the curves. A temperature of 60 K is the minimum acceptable temperature. We have also imposed the constraint that the brightness temperature of the CO($7 \rightarrow 6$) line must be at least 40 K.² This constraint can in principle eliminate a number of models which satisfy the line *ratios*. For the high temperature

²Using the observed *lensed* CO source size in the CO($7 \rightarrow 6$) line (Alloin et al. 1997) indicates a source radius $r \lesssim 0.48h^{-1}m_C^{-1}$ kpc (assuming $q_0 = 1/2$), where $m_C \approx 0.2m$ is the magnification of CO in image C of the quad (m is the total magnification for all four images). The exact relation between m_C and the estimate of the true source radius r is model dependent – here we have assumed that lensing stretches the source predominantly in one dimension; see Burke et al (1991) for an illustration of distortions expected in a quad lens. Given these assumptions, the minimum brightness temperature in the CO($7 \rightarrow 6$) line (that is, for unit areal filling factor) is $T_R(7-6) \gtrsim 40m_C$ K, independent of h .

models, the allowed range in density is a factor of 3 – 10, while for $T = 60$ K any density greater than $n \approx 8 \times 10^4 \text{ cm}^{-3}$ is allowed. The acceptable range of $N_{\text{CO}}/\Delta V$ increases from about a factor of two ($T = 60$ K) to a factor of seven ($T = 300$ K).

At $T = 60$ K, the line ratio constraints can be satisfied for thermalized level populations (which is why there is no upper limit to the acceptable density), provided that the optical depth is not too large ($\tau_{3-2} \lesssim 2$): otherwise the line ratios would simply be the ratio of Rayleigh-Jeans brightness temperatures for $T = 60$ K, which is too large compared to the observed line ratios.³ Thus the ratio of the optical depth terms $(1 - e^{-\tau})$ must be less than one, which requires that the optical depths are not much greater than unity and that τ_{7-6} is less than τ_{3-2} . The sharp cutoff in $N_{\text{CO}}/\Delta V$ at the high end is the result of this optical depth restriction; the boundary is nearly vertical because, except at the lowest densities, the rotational levels are thermalized through $J = 7$ for all the densities.

At high temperatures the line ratios are matched by somewhat different physics. Thermalized levels are unlikely, as the high- J lines would then be too strong relative to $J = 4 \rightarrow 3$ no matter what the optical depths. The observed fall-off to the higher J lines can still be matched in this case, provided that the level populations are subthermal; in particular, the excitation temperatures T_{ex} of the $J = 5$ and $J = 7$ levels must be well below that of $J = 4$. This restricts the density from being too large, and in fact there is only a narrow range (at a fixed temperature) at which the line ratio constraints are satisfied. In addition, the optical depths are also restricted from being too large, as otherwise radiative trapping would inhibit the required decrease in the excitation temperature. It is really the drop in T_{ex} that is crucial, as the optical depths may actually *increase* from the $3 \rightarrow 2$ line to the $7 \rightarrow 6$ line; the drop-off in line flux is then due to the fact that kT_{ex}/E_J is less than \sim unity for the $J = 7$ level, while $T_{\text{ex}}(J = 3)$ is non-negligibly larger than $T_{\text{ex}}(J = 7)$. There is a systematic trend in the line ratios; the model values approach the maximum allowed observational values with increasing $N_{\text{CO}}/\Delta V$.

The maximum optical depth in the $\text{CO}(4 \rightarrow 3)$ line is generally ~ 3 . The relatively low optical depths are mandated by the low value of the $(5 - 4)/(4 - 3)$ and $(7 - 6)/(4 - 3)$ ratio, as outlined above. This result is unusual in comparison to Galactic molecular clouds, where the optical depth in the $\text{CO } J = 1 \rightarrow 0$ line (the most frequently observed transition) is generally inferred to be large. However, modest optical depths in the CO rotational transitions appear to be common in starburst galactic nuclei (Aalto et al. 1995), for the same reason as in our models of the CO emission from the Cloverleaf: the elevated gas temperatures ($T \gtrsim 60$ K) distribute the molecules over a much larger number of rotational levels. In addition, since the Cloverleaf is at a redshift $z = 2.558$, it is possible that the gas-phase metallicity is considerably below the Solar neighborhood value, which will affect the CO abundance and emission (e.g. Maloney & Wolfire 1996). A clear prediction of our single-component CO models is that the $\text{CO}(1 \rightarrow 0)$ line should

³ For example, the R-J brightness temperature ratio for optically thick and thermalized lines at 60 K is 0.89 for $(7-6)/(4-3)$, compared with the observed value of 0.68 ± 0.13 . At 300 K, the thermal R-J ratio is 0.98.

be weak compared to the CO($3 \rightarrow 2$) line, with a brightness temperature about one-third that of the $3 \rightarrow 2$ line; this is a consequence of the increase in optical depth with J up to $J \approx 4$ or 5.

3.2. The CI lines

Our upper limit on the intensity of the CI 809 GHz line gives an upper limit to the $\text{CI}(^3P_2 \rightarrow ^3P_1)/\text{CI}(^3P_1 \rightarrow ^3P_0)$ ratio of ~ 3.9 (here using luminosities L expressed in L_\odot). We have calculated the expected ratio of these lines as a function of density, T , and $N_C/\Delta V$, as for the CO lines. The upper limit to the 809/492 ratio is only significant for gas temperatures $T \gtrsim 100$ K, where it restricts the gas densities to be $n \lesssim 10^4 \text{ cm}^{-3}$. Thus in principle, the CI emission can arise from the same regions which produce the CO emission, as delineated in Figure 2.

The observed ratio of luminosities L in the CI 492 GHz and CO($3 \rightarrow 2$) lines is approximately 0.5 (Table 1). In order to match this ratio, the column density per unit linewidth of neutral carbon must be $N_C/\Delta V \gtrsim 3 \times 10^{17} \text{ cm}^{-2} (\text{km s}^{-1})^{-1}$. Therefore, if the CO and CI emission arise from the same regions, the neutral carbon abundance is comparable to or a few times larger than that of CO. This unusually high ratio of C to CO is a reflection of the rather low ratio of $N_{\text{CO}}/\Delta V$ required to match to CO line ratios.

We can compare the CI/CO ratio for the Cloverleaf with the *COBE* results for the Milky Way (Wright et al. 1991), and extragalactic detections of the 492 GHz line in IC 342 by Büttgenbach et al. (1992), and in M82 by Schilke et al. (1993) and White et al. (1994)⁴. Relative to the CO $J = 2 \rightarrow 1$ line, the flux in the 492 GHz CI line is 1.4 ± 0.4 (IC 342) and 2.3 ± 0.6 (Milky Way). If the CO lines are optically thick, the ratio of the CI line to the CO transitions will scale as ν^{-3} in the high-temperature limit, so that relative to the CO($3 \rightarrow 2$) line these flux ratios are 0.4 (IC 342) and 0.7 (Milky Way), similar to the value of 0.5 seen in the Cloverleaf. From Schilke et al. (1993) and White et al. (1994), the ratio in M82 is 0.7. Büttgenbach et al. (1992) conclude that the ratio seen in IC 342 and the Milky Way is consistent with the bulk of the emission arising in photodissociation regions (PDRs), although Schilke et al. (1993) and White et al. (1994) argue that the ratio is too large compared to standard PDR models; the CI intensity can be enhanced if the PDRs are clumpy or the cosmic-ray flux is very high. Although the CI and CO emission in the Cloverleaf probably do not arise in PDRs (see §3.3 and §4) the similarity in the line ratios is probably a reflection of a similarity in the physical conditions: relatively high temperatures and densities, optically thin CI emission, and (marginally) optically thick CO emission.

⁴Brown & Vanden Bout (1992b) have reported detection of CI in F10214+4724, but at a substantially different velocity from CO($3 \rightarrow 2$). The emission in the two species is therefore unlikely to be cospatial, so we do not cite a CI/CO ratio for this object here.

3.3. The HCN line

Our tentative detection of HCN($4 \rightarrow 3$) indicates a luminosity L' (in K km s $^{-1}$ pc 2) relative to the CO($4 \rightarrow 3$) line of about 0.25, which is similar to the HCN($1 \rightarrow 0$)/CO($1 \rightarrow 0$) ratio seen in ultraluminous galaxies (Solomon, Downes, & Radford 1992b). Except for $T \approx 60$ K, the lowest allowable value, the maximum allowed densities in the CO-emitting region ($n \sim 10^5$ cm $^{-3}$) are far below the effective critical density required to thermalize the HCN($4 \rightarrow 3$) line [$n \approx 10^7$ cm $^{-3}$; even for the HCN($1 \rightarrow 0$) line, the critical density is $n \approx 10^5$ cm $^{-3}$ at these temperatures]. In this case the ratio of HCN and CO luminosities is essentially determined by the sub-thermal excitation of the HCN. (This is also true for models with $T = 60$ K unless the density is extremely high.) This is not a very satisfactory explanation, however, as it requires fine-tuning of the gas parameters to match the observed ratio, and does not explain why a ratio of order 0.2 is characteristic of ultraluminous galaxies. A similar constraint arises from the failure of Wilner et al. (1995) to detect the HCO $^+$ ($4 - 3$) line, implying that most of the gas is not at densities above the effective critical density for this transition, $n_{\text{cr}} \approx 2 \times 10^6$ cm $^{-3}$.

It is more probable that this ratio reflects the fraction of the CO-emitting region which has a density high enough to collisionally excite the HCN line. Solomon, Downes, & Radford (1992b) argue that only star-forming regions in molecular clouds have such high gas densities, and that therefore ultraluminous galaxies are powered by star formation. However, this argument overlooks the fact that in galaxies with powerful active nuclei, such as the Cloverleaf and F10214+4724, there is a large minimum gas pressure which is enforced by the radiation pressure from the AGN.⁵

Assuming that the incident flux from the AGN is absorbed in a region which is thin compared to the thickness of a cloud, then in equilibrium the cloud pressure must at minimum equal the absorbed radiation pressure. In terms of $\tilde{P} = nT$, this constraint can be written

$$\tilde{P}_{\text{min}} = 2 \times 10^{10} \frac{L_{44}}{r_{\text{pc}}^2} \left(\frac{f_{\text{abs}}}{0.1} \right) \text{ cm}^{-3} \text{ K} \quad (1)$$

where the bolometric luminosity of the AGN is $L_{\text{bol}} = 10^{44} L_{44}$ erg s $^{-1}$, the distance of the cloud from the AGN is r_{pc} parsecs, and the fraction of the incident luminosity which is absorbed is f_{abs} . In terms of the gas density rather than \tilde{P} , equation (1) is

$$n_{\text{min}} = 2 \times 10^8 \frac{L_{44}}{r_{\text{pc}}^2} \left(\frac{f_{\text{abs}}}{0.1} \right) T_2^{-1} \text{ cm}^{-3} \quad (2)$$

where the gas temperature $T = 100T_2$ K. The bolometric luminosity of the Cloverleaf is $L_{\text{bol}} \approx 10^{14} m^{-1} h^{-2} L_{\odot}$, where m is the magnification factor. Modelling of the Cloverleaf images

⁵ Here we assume the gas communicates the radiation pressure through much of the molecular column in directly illuminated clouds. This wouldn't necessarily be true with a highly inhomogeneous medium with an effective covering factor far above unity.

suggests that $m \sim 10$ (Kayser et al. 1990) but this is uncertain. Equation (2) predicts that the density will exceed 10^5 cm^{-3} [enough to collisionally excite the HCN($1 \rightarrow 0$) line] within a radius

$$r = 8.8 \times 10^2 \left(\frac{m}{10} \right)^{-1/2} T_2^{-1/2} \left(\frac{f_{\text{abs}}}{0.1} \right)^{1/2} \text{ pc.} \quad (3)$$

For $n \gtrsim 10^7 \text{ cm}^{-3}$, needed to excite the HCN($4 \rightarrow 3$) line, the numerical coefficient is smaller by a factor of ten. The apparent line fluxes for transitions which require very high densities to excite are likely to be significantly affected by differential magnification, as they will arise preferentially at small radii.

An alternative possibility which may be generically important in infrared-luminous galaxies – either starbursts or AGNs – is that the HCN levels are not collisionally excited, but instead are populated through absorption of $14\mu\text{m}$ photons in the degenerate bending mode (e.g., Aalto et al. 1994). For optically thin HCN emission (no radiative trapping), the criterion for radiative pumping of the HCN($4 \rightarrow 3$) line to be significant is that the dust temperature fulfills the condition

$$T_d \gtrsim 1025 [\ln(487W + 1)]^{-1} \text{ K} \quad (4)$$

where the continuum has been assumed to be a Planck function multiplied by a dilution/optical depth factor W . For $W = 1$, equation (4) requires $T_d \gtrsim 166 \text{ K}$; for $W = 0.1$, $T_d \gtrsim 262 \text{ K}$. Substantial amounts of dust at these temperatures are undoubtedly present in the Cloverleaf (Barvainis et al. 1995). We note that these two mechanisms predict rather different size scales for the HCN emission; from equation (3), radiation pressure will only keep the gas density high enough to collisionally excite the HCN($4 \rightarrow 3$) line to a radius of 100 pc, whereas for a bolometric luminosity of $10^{13} L_\odot$, the dust temperature will be above 250 K to more than 300 pc distance. We might also expect that in the former case, the HCN and CO line profiles could differ significantly; testing this will require much higher signal-to-noise observations than are presently available.

4. Discussion and Conclusions

The presence of a luminous active nucleus appears to have profoundly influenced the state of the interstellar medium in the Cloverleaf. The high line luminosities, the high ratio of CI to CO line intensities, and the prominent HCN emission may be the result of the impact of the radiation from the AGN on the surrounding molecular clouds.

The mass of gas in the Cloverleaf can be estimated from both the CO line observations and the CI 492 GHz line. The total molecular gas mass can be derived from an observed CO line luminosity and our detailed model results as

$$M_{\text{H}_2}(\text{CO}) = L_{\text{CO}}(M_{\text{cl}}/L_{\text{cl}}) \approx 215 L_{\text{CO}} \frac{10^{-17}(N_{\text{CO}}/\Delta V)}{(y_{\text{CO}}/3 \times 10^{-5})} (\nu I_\nu)^{-1} M_\odot \quad (5)$$

where $N_{\text{CO}}/\Delta V$ is in $\text{cm}^{-2} \text{ km}^{-1} \text{ s}$, ν is the rest frequency of the transition, I_ν is the intensity at line center emerging from a cloud, and y_{CO} is the CO abundance by number relative to total

hydrogen; $M_{\text{cl}}/L_{\text{cl}}$ is the mass-to-CO luminosity ratio of the clouds from our models. Using the observed luminosity of the CO($3 \rightarrow 2$) line of $L_{\text{CO}}(3-2) = 1.0 \times 10^8 m^{-1} h^{-2} L_{\odot}$, we find a molecular gas mass $M_{\text{H}_2} \approx 2 \times 10^{10} m^{-1} h^{-2} M_{\odot}$, essentially independent of the choice of model, (except for the highest column density, high-temperature models, where it can be as large as $M_{\text{H}_2} \approx 6 \times 10^{10} m^{-1} h^{-2} M_{\odot}$). This is an order of magnitude smaller than the value originally suggested by Barvainis et al. (1994), due to the considerably higher emissivity of warm CO of modest optical depth.

To estimate the gas mass from the CI emission, we assume that the 492 GHz line is optically thin. Over the allowed range of physical conditions (see §3.2) approximately 40% of the carbon atoms are in the $J = 1$ level of the ground 3P state. Using an Einstein A -coefficient of $7.9 \times 10^{-8} \text{ s}^{-1}$ (Nussbaumer 1971), we find that the mass of hydrogen associated with the CI is then

$$M_{\text{HI}}(\text{CI}) \simeq 1400 \frac{L_{492}}{(y_{\text{C}}/3 \times 10^{-5})} M_{\odot} \quad (6)$$

where the line luminosity L_{492} is in L_{\odot} and y_{C} is the carbon abundance by number. (In both equations [5] and [6] we have normalized to a carbon abundance of 1/10 solar; equation [5] assumes all carbon is in CO.) The observed line luminosity $L_{492} = 5.8 \times 10^7 m^{-1} h^{-2} L_{\odot}$, and so we obtain a gas mass $M_{\text{HI}}(\text{CI}) \approx 8 \times 10^{10} m^{-1} h^{-2} M_{\odot}$.

If irradiation by the central source is important in pressurizing the clouds, there will be associated dynamical effects, as the radiative momentum imparted to the clouds will provide an outward acceleration. Scoville et al. (1995) suggested that support of the molecular gas against its own self-gravity by radiation pressure could be important in F10214+4724, in order to reconcile the fact that their derived molecular mass exceeds the dynamical mass (estimated from the measured CO size and linewidth) by an order of magnitude. We estimate M_{dyn} for the Cloverleaf from the upper limit to the CO source size r (see footnote 2) and the observed linewidths:

$$M_{\text{dyn}} \approx \frac{r \Delta V_{\text{FWHM}}^2}{G \sin^2 i} \approx 1.6 \times 10^{11} m^{-1} h^{-1} M_{\odot}, \quad (7)$$

where the inclination angle i has been taken to be 45° . Comparison with the above expressions for the masses derived from CO and CI shows that the gas mass is in both cases smaller than the dynamical mass (assuming, of course, that r is not much smaller than the current upper limit, and that the carbon abundance is not much less than 1/10 solar). Although radiation pressure support could be important in the Cloverleaf, it is not at present necessary to appeal to it.

The gas mass derived from the CI observations is $\sim 1.3 - 4$ times larger than the molecular gas mass estimated from CO; either the hydrogen associated with the atomic carbon dominates the gas mass (plausibly a result of the high X-ray ionization and heating rates within a few kpc of the active nucleus: Maloney, Hollenbach & Tielens 1996), or else the CI emission is being differentially magnified by the lensing relative to the CO. In either case, the gas mass is substantial, but not extreme, especially as the total magnification m may be a factor of ten. The detectability of the Cloverleaf in CO and CI would appear to be the result not of an enormous mass of gas, but rather

the effects of gravitational lensing and the rather unusual physical conditions (high emissivities) in the gas, in consequence of the proximity of a luminous active nucleus.

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FIGURE CAPTIONS

Fig. 1.— CO, CI, and HCN lines from the Cloverleaf quasar, shown with Gaussian fits to the line profiles. See Table 1 for line parameters derived from the fits. The CO($7 \rightarrow 6$) parameters have been estimated by fixing the gaussian-fitted line width to the mean of the other CO lines, as described in §2 of the text.

Fig. 2.— Allowed regions of CO column density per unit linewidth versus molecular hydrogen density for three temperatures, based on non-LTE escape probability modelling of the CO line ratios. See text for discussion.

Table 1. Millimeter Line Observations of the Cloverleaf. ^a

Line	$\nu_{\text{obs}}^{\text{b}}$ (GHz)	T_A^* (mK)	S_ν (mJy)	ΔV_{FWHM} (km s ⁻¹)	V^{c} (km s ⁻¹)	I (Jy km s ⁻¹)	$L / 10^8$ (L_\odot)	$L' / 10^{10}$ (K km s ⁻¹ pc ²)
CO(3 → 2)	97.199	4.2(0.3)	25.8(1.6)	362(23)	−29(12)	9.9(0.6)	1.8(0.1)	13.4(0.8)
¹³ CO(3 → 2)	92.924	< 1.1	< 6.7	< 2.4	< 0.4	< 3.6
CO(4 → 3)	129.576	7.8(0.3)	52.7(2.0)	375(16)	+12(7)	21.1(0.8)	5.1(0.2)	16.1(0.6)
CO(5 → 4)	161.964	7.2(0.4)	55.6(3.2)	398(25)	+5(12)	24.0(1.4)	7.2(0.4)	11.7(0.7)
CO(7 → 6)	226.721	...	109(5)	...	−5(13)	47.3(2.2)	18.3(0.9)	10.9(0.5)
Cl(³ P ₁ → ³ P ₀)	138.351	1.1(0.1)	7.7(0.8)	430(46)	−47(24)	3.6(0.4)	0.9(0.1)	2.4(0.3)
Cl(³ P ₂ → ³ P ₁)	227.510	< 2.2	< 22.2	< 8.5	< 3.6	< 2.1
HCN(4 → 3)	99.631	0.9(0.2)	5.5(1.1)	436(103)	+49(40)	2.6(0.5)	0.5(0.1)	3.4(0.6)

^aLine parameters derived from Gaussian profile fits. Quoted uncertainties are statistical only. For CO(7 → 6), the line strength was estimated from measurements taken at the Plateau de Bure Interferometer assuming a line FWHM of 376 km s⁻¹, as described in §2 of the text. Upper limits are 3 σ , and were derived from Gaussian fits with the linewidth and redshift fixed to the mean values for the detected lines. Line luminosities assume $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$, and are *not* corrected for gravitational magnification; see text.

^bObserved frequency of line centroid.

^cVelocities measured relative to $z = 2.5579$, which is the weighted average redshift of the four detected CO lines.



